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**DEFORMATION OF GEODETIC NETWORK IN THAILAND DUE TO
CRUSTAL MOVEMENT**

**Submitted by Royal Thai Survey Department
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Deformation of Geodetic Network in Thailand due to crustal movement

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Abstract

The Mw 9.3 mega-thrust earthquake on December 26th, 2004 off the coast of North Sumatra, has resulted in large co- and post-seismic motions throughout SE Asia. As a result, also the geodetic network of Thailand has been deformed. The THAICA network has been regularly observed with GPS since 1994. Therefore the continuous tectonic motions in Thailand, which is located on the Sundaland block are well known. The last GPS campaign prior to the mega-thrust earthquake took place in October 2004 as part of the EU-ASEAN funded SEAMERGES project. Shortly after the earthquake, the GPS campaign was repeated in February 2005 to determine the co- and post-seismic. The entire THAICA and GEODYSSEA GPS database on Thailand was (re)processed, using the Precise Point Positioning strategy of the JPL GIPSY software package. Data from the International GPS Service (IGS) were included, to obtain the positions and velocities of the Thai sites in the International Terrestrial Reference Frame (ITRF) solution of 2000. The coordinate time series of the Thai geodetic network span up to a decade and each GPS campaign averaged position was determined with an absolute horizontal accuracy of 3 to 5 mm in ITRF-2000. This resulted in absolute steady-state velocities prior to the earthquake with uncertainties below 1 mm/yr. The earthquake resulted in co-seismic displacements, ranging from 27 cm in the south, 8 cm in the center, to about 3 cm in the north and east of Thailand. The post-seismic motion already increased further these displacements at each location by 25% in only 50 days. The post-seismic motion is time dependent with an exponential decay rate, and will be clearly detectable for at least 0.5 year in the north and east of Thailand, and up to 1.5 year in the south. The relative position changes in the national Thai geodetic network can finally reach up to 50 cm or even more if more large aftershocks like the Mw 8.7 earthquake in Sumatra occur. Additional GPS re-measurements are required to model the post-seismic motion better, and determine accurate time dependent transformation parameters between pre- and post-earthquake network coordinates.

1. Introduction

The giant earthquake of December 26, 2004 off the northern coast of Sumatra, Indonesia had dramatic consequences for the region. The earthquake triggered a big tsunami in the Indian ocean, which hit many coastal regions in the surrounding countries, where giant waves and flooding may have killed up to 300,000 people and have affected the lives of many more (Vigny and The SEAMERGES participants, 2005). But also further inland the earthquake has changed the landscape. Although not creating any danger to the people living there, many regions in SE Asia have been displaced and deformed at the centimeter to meter level. This position shift of land masses decreases with the distance to the earthquake epicenter, but in the case of a Mw 9.0, possibly even Mw 9.3 earthquake (Stein and Okal, 2005), remains significant up to a couple thousand kilometers away (Vigny et al., 2005). Therefore, all geodetic networks within this region were deformed during the earthquake (co-seismic), and will continue to deform (post-seismic) for at least many months and possibly even years to come. In this report we focus on the geodetic network of Thailand, using GPS data from the THAICA network (Fig. 1) of the Royal Thai Survey Department (RTSD), which has been regularly measured since 1994. This was also done in October 2004, at a relatively short time period before the earthquake occurred. The complete THAICA network was also re-measured in February 2005.

A detailed description and the background of the earlier GPS measurements in Thailand is given in the 2001 and 2002 reports from DEOS to RTSD (Simons and Ambrosius, 2001, 2002). More information on the THAICA network and the 1994/1996 GPS campaigns can be found in (Mingsamon et al.1998). Because most points of the THAICA network have long coordinate time series, their absolute coordinates and velocities were well known prior to the earthquake. Because there were no observations made during the earthquake, only displacements which include both co- and post-seismic motion could normally be computed. However, because permanent data from the Department of Survey and Mapping Malaysia (DSMM) is available during both the THAICA observation periods, and also on the days shortly

before and after the earthquake, it is possible to differentiate between the co-seismic and post-seismic displacements at the THAICA network sites.

In this report first the GPS measurements will be briefly discussed. This is followed by the GPS analysis of all the available THAICA data between 1994 and 2005. The network positions and velocities prior to the earthquake are computed. Next the positions after the earthquake are determined, and the amount of co-seismic and post-seismic displacements estimated. A model for the co-seismic deformation of Thailand is computed, and an estimates for the future post-seismic motions are given.
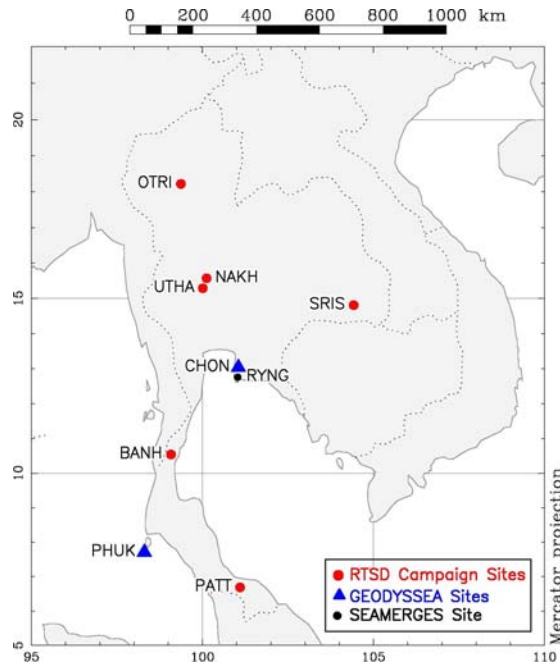

Fig. 1 The THAICA Network in Thailand

Table 1. Overview GPS data used from GPS Field Campaigns

GPS Campaign	P H U K	C H O N	U T H A	B A N H	S R I S	O T R I	P A T T	N A K H	R Y N G
Observed GPS stations									
Before earthquake									
THAICA-94*	X	X	X	X	X	X	X		
GEODYSSEA-94*	X	X	X						
THAICA-96*				X	X	X			
GEODYSSEA-96*	X	X							
GEODYSSEA-98	X	X							
RTSD-00	X	X	X						
RTSD-01	X	X	X	X	X	X	X		
RTSD-02	X	X	X	X	X	X	X	X	
RTSD-04	X	X	X	X	X	X		X	X
After earthquake									
RTSD-05	X	X	X	X	X	X		X	X

*: campaigns carried out in same period. PATT in 2001 is new site.

2. GPS Field Campaigns and other used GPS data

An overview of all THAICA data used between 1994 and 2005 is given in Table 1. More details on the 1994-2002 measurements can be found in (Simons and Ambrosius, 2001, 2002).

In the framework of the EU-ASEAN funded "SE Asia: Mastering Environmental Research using GEodetic Space Techniques" (SEAMERGES) project, RTSD has made GPS observations on 5 THAICA network locations from 25 to 31 October 2004. Also the 2 GEODYSSEA sites at Chonburi and Phuket were observed simultaneously, together with a new semi-permanent SEAMERGES GPS station (RYNG) in Ban Chang, Rayong. All stations were observed for a period of 7 days, using dual frequency GPS receivers from both Trimble and Leica, of which 2 were provided by Chulalongkorn University and DEOS.

Shortly after the mega-thrust earthquake of December 26th, 2004, it was clear that large co-seismic displacements also had affected Thailand (Vigny and The SEAMERGES participants, 2005). Therefore RTSD, Chulalongkorn University and DEOS decided it was important to re-measure all THAICA sites. This was done already mid-January for the GEODYSSEA point in Phuket, and a location at Chulalongkorn University which was also measured during the October 2004 GPS campaign. The results (Trisirisatayawong, 2005) confirmed that Thailand was affected, with Phuket shifted as much as 32 cm, and Bangkok with almost 9 centimeter. These GPS measurements are not discussed in this report, which focuses on the analysis of a complete repeat of the October 2004 GPS observations.

From 10-15 February 2005, RTSD organized a 5 - day re-occupation of all GPS sites thereby using for each location the same GPS receiver and antenna as during the October 2004 measurements. This was done to minimize the position error due to the use of different GPS antennae. Also the SEAMERGES GPS station in Rayong was operational during this time. Again both Chulalongkorn University and DEOS provided some of their Leica GPS receivers.

For each campaign, data from the Malaysian permanent GPS network was provided by DSMM. The MASS network currently consists of 17 GPS stations, located both on the peninsular Malaysia and Sabah and Sarawak on East-Malaysia. These stations were also operational during the earthquake, and by including them, the amount of post-seismic motion can be estimated as will be explained in the next section.

Because of the wide-spread deformation, a local or national reference frame can not be used to present the latest coordinates and displacements. Therefore a number of permanent GPS stations from the International GPS Service (IGS) need to be included, so that the geodetic results can be given in the global International Terrestrial Reference Frame (ITRF) solution of 2000 (Altamimi et al., 2002). Previous experience with mapping local networks in SE Asia (Wilson et al.,1998; Simons et al.,1999; Michel et al.,2001) into ITRF has shown that if only regional IGS stations are selected the mapping may not always be optimal, and position and velocity errors may occur. The main reason is that even today, the available IGS network with valid ITRF-2000 solutions in SE Asia remains limited. Moreover, some stations have been affected by nearby earthquakes, and hence they don't always fit the linear velocity trend given by ITRF, nor are official position jumps made available. Because ITRF gives a velocity estimate together with position at a certain reference epoch (01-01-97 in the last two ITRF solutions), any errors in the predicted position become larger as the analyzed GPS data lies further away from the actual time series used in ITRF-2000. This is especially true for (new) IGS stations which only had short time series included in ITRF-2000. Therefore a regional mapping strategy into the ITRF-2000 can be adversely affected, which is not always immediately visible, because with few regional IGS sites available part of the position misfits can be absorbed by the Helmert transformations, which are commonly used in the combining of network solutions.

To avoid the above mentioned mapping problems, a number of well determined global IGS sites are also included in the analysis. In total, IGS data from 16 regional and 17 global stations (Fig. 2) were retrieved for each campaign period from the IGS databases (http://igscb.jpl.nasa.gov, (Beutler et al., 1994)).
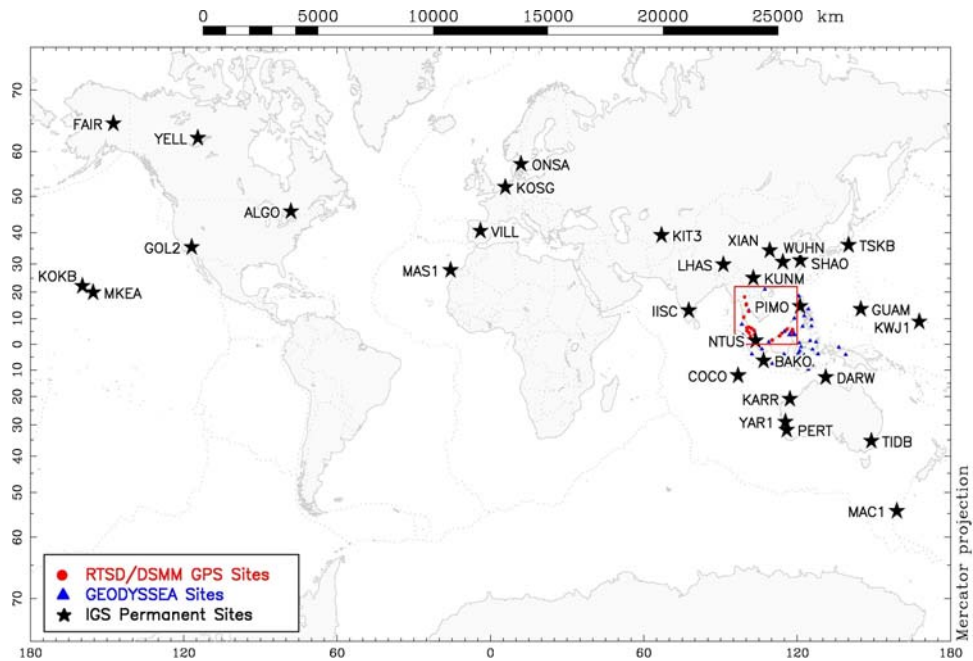
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Fig. 2 GPS stations included from the IGS network.

3. GPS Data Analysis

For the complete data set from 1994 to 2005, daily fiducial-free network solutions were computed with the GIPSY precise point positioning (PPP) strategy (Zumberge et al., 1997). With this strategy, each station position can be solved for individually, using precise (JPL) satellite orbits, satellite clocks and corresponding earth rotation parameters (ftp://sideshow.jpl.nasa.gov). Because the orbits and clocks are held fixed in this technique all correlations among the different stations are not explicitly computed. Therefore a network can be processed much more efficiently than the traditional technique of processing the entire network simultaneously. The complete software package and additional tools are currently installed at the Department of Survey and Engineering of Chulalongkorn University, and RTSD officers have received training in the framework of the LOA between RTSD and DEOS and as part of the SEAMERGES project.

3.1 Daily station coordinate solutions

The individual PPP station coordinate solutions were computed using the ionosphere-free linear combination of the zero-differenced GPS phase and pseudorange data at 5 minute intervals with an elevation cut-off angle of 15 degrees. To account for tropospheric effects, the zenith path delay (using Niel's model (Niel, 1996)) and gradients are estimated at each time interval. Data from GPS satellites that were undergoing maintenance during part of the processed day (ftp://tycho.usno.navy.mil/pub/gps/) were removed. Ocean loading modeling parameters for all site locations were obtained from H.-G. Scherneck and M.S. Bos (http://www.oso.chalmers.se/˜loading/ (Scherneck, 1991)) Finally, because different antennae were used in the network, the NGS relative antenna phase center corrections (http://www.ngs.noaa.gov/ANTCAL (Mader, 1998)) were applied. In a final processing step, all individual solutions are merged into one daily covariance band matrix (no correlations between different stations), after which the ambiguities can be resolved. This is the only stage at which GIPSY relies on double differences from the ionosphere-free combined GPS phase and pseudorange measurements. Current software memory requirements prevent ambiguities from being solved in one step for large networks. Therefore, the ambiguities are resolved in successive iterations, where the shortest baselines are solved for first (boot-strapping), using a sequential wide- and narrow-laning approach to fix the phase biases to the correct integers. When the iterations are completed, the daily covariance matrix is updated, and now has become a full matrix, due to the correlations introduced in the ambiguity fixing procedure.

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3.2 Multi-day averaged campaign solutions

The daily PPP coordinate solutions were combined into campaign averaged coordinate solutions whereby any systematic differences between the various daily network solutions are eliminated by computing optimized 7-parameter Helmert transformations using a least squares adjustment. In this process, any daily station solutions identified as outliers are downweighted and the obtained daily coordinate repeatabilities give a realistic indication of the internal accuracy of the network processed. The formal errors, which typically are underestimated in the GIPSY PPP strategy, are scaled using the overall repeatability of each averaged solution. This results in realistic errors, which in turn, will result in more realistic formal errors in the site velocity estimation, and automatically weighs the contribution of each campaign/ weekly averaged solution.

Table 2. Daily Coordinate Repeatabilities 2004 and 2005 GPS Campaigns

Stations	Station Solutions	RMS Residuals (mm)		
		North	East	Up
2004				
PHUK	7 (-0)	2.2	3.6	6.7
CHON	7 (-0)	2.6	1.9	6.6
SRIS	7 (-0)	0.7	1.6	4.9
BANH	7 (-0)	2.2	3.2	12.5
UTHA	7 (-0)	0.7	1.5	3.4
OTRI	7 (-0)	0.9	3.1	5.2
NAKH	7 (-0)	1.4	2.3	8.9
RYNG	7 (-0)	0.9	1.4	5.1
RTSD (8)	56 (-0)	1.6	2.5	7.2
DSMM (12)	78 (-1)	2.1	3.9	8.4
IGS (32)	221 (-1)	1.5	2.7	5.4
Total (7d)	355 (-2)	**1.6**	**2.9**	**6.5**
2005				
PHUK	5 (-0)	1.2	1.5	1.8
CHON	5 (-0)	0.9	1.4	12.2
SRIS	5 (-0)	1.4	3.0	6.5
BANH	5 (-0)	1.0	1.9	9.7
UTHA	5 (-0)	0.4	1.3	6.9
OTRI	4 (-0)	0.4	3.7	5.6
NAKH	5 (-0)	0.4	1.7	8.1
RYNG	7 (-0)	1.3	1.7	8.0
RTSD (8)	41 (-0)	1.0	2.1	7.9
DSMM (11)	60 (-1)	1.6	3.7	6.1
IGS (27)	184 (-1)	1.5	2.8	6.4
Total (7d)	285 (-2)	**1.4**	**2.9**	**6.6**

The daily station coordinate repeatabilities for each Thai station, together with the number of final and removed station coordinate solutions, are given in Table 2 for the 2004 and 2005 GPS campaigns. Besides the overall Root-Mean-Square (RMS) of the daily station coordinate residuals with respect to the multi-day averaged campaign solutions for the complete network, the RMS statistics are also shown for the RTSD (including the Thai GEODYSSEA and SEAMERGES sites), DSMM and the IGS stations. The daily repeatabilities range from 1 to 3mm for the horizontal position and from 5 to 8mm for the height. The coordinate repeatabilities for PHUK are significantly better in 2005, possible due to the cutting of a nearby palm tree which was obstructing the visibility. In summary, the internal precision of the Thai sites is quite high, comparable to the performance of the IGS network sites and the present 'state-of-the-art' level of high precision GPS data processing.

3.3 Mapping solutions in ITRF-2000

Each multi-day averaged campaign solution was projected onto ITRF-2000 coordinate sets, each containing the positions of the included IGS stations at the middle epoch of each analyzed

week/campaign. The ITRF-2000 GPS SINEX file (http://lareg.ensg.ign.fr) is propagated to each of these epochs, and contains the full covariance matrix for the IGS stations subset. Typically, 15-20 IGS stations were used in the mapping (Table 3) of each multi-day averaged campaign solution. For various reasons, the other IGS stations were not used in the mapping, but were treated similarly as the stations of the Thai and Malaysian network. BAKO, NTUS and PIMO were left free to adjust because they reside in the region of interest and might be affected by local deformation signals. MKEA, KARR, SHAO and KUNM were also left free to adjust in order to check the quality of the mapping, and DARW and XIAN because they are relatively young stations. Finally, COCO, KOKB, TSKB, GUAM, GOLD, FAIR and KOSG were automatically rejected during the mapping process because of unreported jumps in their coordinate time-series. These can often be traced back to co-seismic displacements and/or antenna type/setup changes. The coordinate residuals in Table 3 (differences between the ITRF-2000 predicted and the post-mapping station positions) provide an indication of the quality of the mapping. The residuals are small and consistent with RMS values of 2 to 3 mm for the horizontal and about 8 mm for the vertical position. An exception is the 2005 field campaign, were a number of IGS stations were not available. Since 2000, also a decrease in the available IGS sites for mapping can be observed because coordinate time series jumps occurred for a number of sites. Therefore, finally an updated ITRF solution with well defined position jumps will be required in the future. The results of Table 3 together with the daily coordinate repeatabilities of the Thai GEODYSSEA and THAICA sites, indicate that the global (absolute) accuracy with respect to ITRF-2000 of the 2004 and 2005 campaign solution is about 3.5 to 6 mm for the horizontal position, and around 1.5 to 2 cm for the height. The re-processed data from 1994 to 2002 shows similar results. With a time interval of up to 10 years (not including the 2005 campaign results after the earthquake), very accurate estimates of the horizontal site motions in Thailand can be obtained. The December 2004 earthquake has changed these continuous motions, and they will remain polluted with post-seismic motions for many months to even a couple years.

Table 3. Residuals ITRF-2000 transformation for the used IGS sites.

Campaign Solutions	IGS Stations finally used	RMS Residuals (mm)		
		North	East	Up
Before earthquake				
GEODYSSEA/THAICA-94	15 (-0)	**1.7**	**2.3**	**8.8**
GEODYSSEA/THAICA-96	20 (-1)	**2.7**	**3.1**	**9.2**
GEODYSSEA-98	21 (-0)	**1.8**	**2.2**	**5.6**
RTSD-00	19 (-2)	**2.0**	**2.8**	**6.9**
RTSD-01	17 (-3)	**1.7**	**1.9**	**6.5**
RTSD-02	15 (-1)	**2.4**	**2.4**	**7.3**
RTSD-04	15 (-3)	**2.5**	**3.0**	**7.6**
After earthquake				
RTSD-05	10 (-3)	**2.1**	**2.5**	**12.2**

3.4 Pre-Earthquake Velocity estimates in ITRF-2000

In this report first the steady-state site velocities prior to the earthquake are given. These can be easily estimated by computing a (linear) fit through all ITRF- 2000 mapped station coordinates and checking the coordinate residuals at each point in the time series. The velocity differences between this solution and the ITRF-2000 for the included IGS stations were verified both for IGS stations that were and were not used in the mapping process.

The total RMS of the coordinate residuals for all the RTSD, DSMM and IGS sites with respect to their estimated linear trend fitting are about 2, 3 and 8 mm for the north, east and vertical position components, and all are within the range of the absolute accuracy of the station positions.

The complete velocity field for Thailand prior to the earthquake is given in Fig. 3, together with their formal (1-σ) uncertainties of typically 0.2 to 0.5 mm/yr in the horizontal direction. The uncertainties are larger for PATN and NAKH since these sites were only measured twice with a 1 and 2 year time interval.
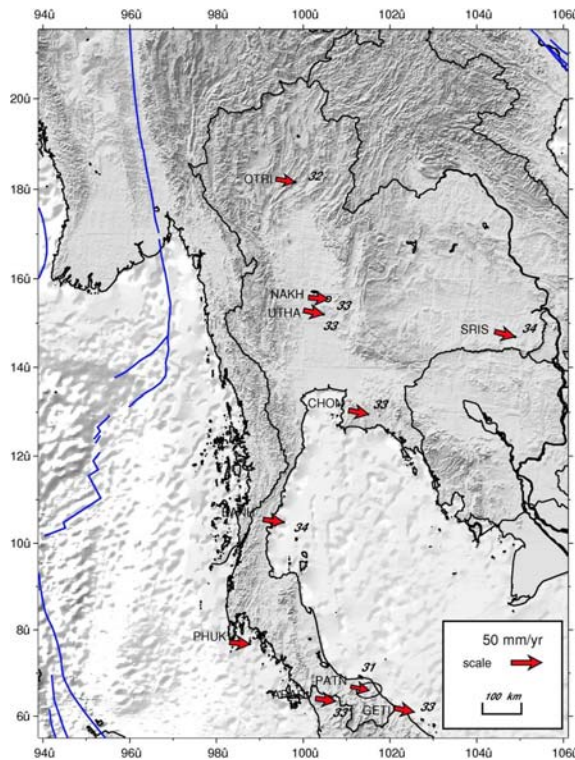
Fig. 3 Thailand 1994-2004 Horizontal Velocities in ITRF-2000.

The IGS stations in and near SE Asia that were not included in the mapping, were used to further validate the quality of the mapping. They all show good linear fits with few outliers and their performance is similar to that of the other regional and global sites. Finally, in order to better assess the accuracy of the station velocities, the velocities estimated for the IGS stations are compared with the ones from ITRF-2000. It should be pointed out that nowhere throughout the GPS data analysis IGS stations were constrained to their ITRF-2000 positions and velocities. The velocity differences are typically below 1 mm/yr for the horizontal and a few mm/yr for the vertical components. An exception are the stations BAKO, NTUS, PIMO and DARW for which the velocities computed in this analysis are more accurate than in ITRF-2000, since they are based on longer time series.

With the final ITRF-2000 coordinates (reference date 25/12/04) and velocities for the THAICA and Thai GEODYSSEA sites available, the Thailand zero order national network can be computed at any epoch in time before the earthquake occurred, and transformation parameters with other existing Thai reference frames (e.g. INDIAN 1975) can be computed. Thailand is located on the stable and rigid part of the Sundaland block (Simons et al., 1999; Michel et al., 2001; Simons et al., 2004) and hence it's motion can be described with an Euler rotation pole. This is a useful technique to model the motion of a tectonic block in an absolute reference frame or with respect to neighboring blocks and can be determined from the velocity field. In (Simons et al., 2004) a pole estimation was done, based on 27 out of 40+ candidate sites on Sundaland, which include the Thai sites discussed in this paper. The Sundaland block covers Indochina peninsula, the Malaysian peninsula, the Sunda shelf, the major part of Sumatra, Java and Borneo. The results (Simons et al., 2004) show that the Sundaland block rotates clockwise at a rate of 0.341 ° /Myr about a pole located 48.9 ° S and 85.8 ° E in ITRF-2000. This rotation is also clearly visible for Thailand in Fig. 3. The advantage of this rotation pole solution for geodesists is that the angular velocities can now be computed for any location on Thailand, which can be useful in geodetic networks in which not all the points have been measured long enough to compute absolute velocities, and to combine and unify different networks that were not measured simultaneously and/or in the same time period.

The pre-earthquake THAICA and Thai GEODYSSEA site coordinates and velocities in ITRF-2000 at 25 December 2004 are given in Appendix A.

4. Displacements due to the mega-thrust earthquake

The mega-thrust earthquake has resulted in a surface deformation of Thailand. This deformation consists of 2 components: co-seismic and post-seismic displacements. The co-seismic component occurred within 10 minutes after the earthquake, immediately followed by post-seismic motion (in the same direction) which follows an exponential decay pattern and typically lasts for months or even years. The post-seismic displacement can equalize the amount of co-seismic displacement, and may even exceed it because there is few historical data on the post-seismic displacements caused by a Mw 9.3 earthquake. Therefore the post-seismic motion needs to be monitored for a long period in time.

The GPS campaign measurements by RTSD took place at the end of October 2004 and the middle of February 2005. This is a 3.5 months time interval, and hence the difference in position has 3 components: continuous, co-seismic and post-seismic motion. The first component is known, and discussed in the previous section. Because there is no data shortly before and after the earthquake, the amount of co-seismic and post-seismic motion can not be directly computed, but only their sum. However, the MASS stations in Malaysia have been operational throughout the entire period, and their co-seismic displacements are very well known (Vigny et al., 2005). Also the ratio between post-seismic and co-seismic motion at each site location in Thailand and Malaysia can be assumed constant in a first approximation. The stations are all located on the Sundaland block, and they all are located at approximately the same distance range from the earthquake (500-1500 km).

The difference in position for the sites observed by RTSD can be obtained from subtracting the 2 campaign solutions, since they are both mapped in the ITRF-2000. The coordinate differences obtained for each of the analyzed Thai sites are given in Table 4 under heading A. The vertical components are also shown, but they are not relevant as they are within the vertical displacement inaccuracies and also the earthquake has not generated any (detectable) vertical motions in Thailand.

Table 4. Station coordinate changes since October 2004

Station	Displacements (cm)			
	2D	North	East	Up
A: Total				
PHUK	33.1	-12.7	-30.4	-1.3
BANH	20.6	-9.4	-18.3	1.2
RYNG	9.6	-4.8	-8.2	1.3
CHON	9.1	-4.9	-7.5	-0.6
UTHA	7.1	-5.0	-4.9	-0.9
NAKH	6.8	-5.6	-3.9	-0.7
SRIS	4.0	-2.5	-3.1	0.6
OTRI	3.5	-3.1	-1.6	2.5
B: Continuous (3.5 months)				
PHUK	1.0	-0.1	1.0	0.2
BANH	1.0	-0.1	1.0	0.1
RYNG	1.0	-0.2	1.0	0.1
CHON	1.0	-0.2	1.0	0.1
UTHA	1.0	-0.2	1.0	0.1
NAKH	1.0	-0.1	1.0	-0.2
SRIS	1.0	-0.3	1.0	0.2
OTRI	1.0	-0.2	1.0	-0.0
C: Co-seismic (within 10 minutes)				
PHUK	27.2	-10.1	-25.2	-1.2
BANH	17.2	-7.5	-15.5	0.9
RYNG	8.3	-3.7	-7.4	0.9
CHON	7.8	-3.8	-6.8	-0.6
UTHA	6.2	-3.9	-4.7	-0.8
NAKH	5.9	-4.4	-3.9	-0.4
SRIS	3.7	-1.8	-3.3	0.3
OTRI	3.2	-2.3	-2.1	2.0

D: Post-seismic (after 50 days)

PHUK	6.7	-2.5	-6.2	-0.3
BANH	4.2	-1.8	-3.8	0.2
RYNG	2.0	-0.9	-1.8	0.3
CHON	1.9	-0.9	-1.7	-0.1
UTHA	1.5	-0.9	-1.2	-0.2
NAKH	1.5	-1.1	-1.0	-0.1
SRIS	0.9	-0.4	-0.8	0.1
OTRI	0.8	-0.6	-0.5	0.5

Note: Aneu = Bneu + Cneu + Dneu

The absolute displacements due to the continuous tectonic motions were computed and are shown under heading B in Table 4. They are about 1 cm for all stations, with a direction identical to the velocity vectors in Fig. 3. These motions need to be removed from the coordinate differences, after which the sum of the co- and post-seismic displacements at the time of the 2005 re-measurement is obtained (the sum for each station of headings C and D in Table 4.

In order to distinguish between the amount of co- and post-seismic motion for the Thai sites, the co-seismic displacements for the Malaysian MASS stations (ARAU and KUAN), the Singapore IGS station (NTUS) and the Indonesian station on Sumatra (SAMP) (Vigny et al., 2005) were compared to the total accumulated (co-seismic plus post-seismic) displacement in February 2005. This was possible because GPS measurements of these stations were available and analyzed together with the Thai data of October 2004 and February 2005. These four stations all indicate that about 80% of the measured displacements is co-seismic, and therefore the remaining 20% is the post-seismic motion up to mid February 2005. These ratio's were applied for the Thai sites, and resulted in the co-seismic and post-seismic displacements given under headings C and D in Table 4. The results agree very well with those of nearby permanent sites in Thailand operated by the Department of Geology of Chulalongkorn University (Vigny et al., 2005). For these stations the co-seismic displacement could be directly estimated from GPS data spanning two weeks before and after the December 2004 earthquake.
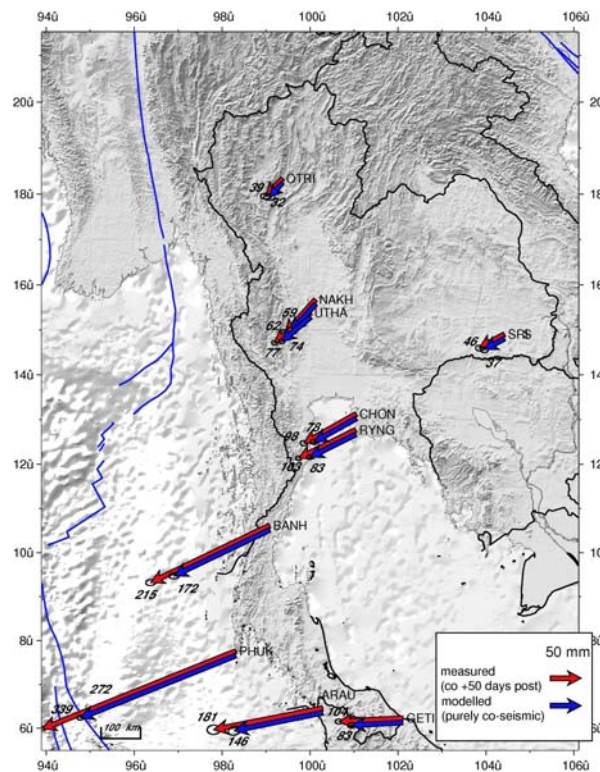

Fig. 4 Co- and post-seismic deformation measured at Thai sites.

The measured (co-seismic+post-seismic) displacements, and the estimated co-seismic displacements are shown in Fig. 4. Clearly the southern part of Thailand, being closest to the earthquake epicenter is deformed most, with Phuket shifted 27 cm (co-seismic) during the earthquake, and displaced already 6 cm more (post-seismic) by mid-February. Although the amount of co- and post-seismic motion decreases towards the center (Bangkok 8 cm co-seismic and already 2 cm post-seismic) and the northeast of Thailand, still displacements larger than 3 cm were detected at Lampang and Srisakhet stations. It therefore is clear that the entire geodetic network has been significantly deformed, with relative position changes between control points up 30 cm. This will even increase to about 50 cm when the post-seismic motions have settled down after 1 to 3 years. This number can even increase further if some of aftershocks in the region are large enough to result in additional co- and post-seismic motions. This already has happened due to the March 28th, 2005 Mw 8.7 earthquake near Sumatra, which shifted the southern part of Thailand by another 2-3 cm based. This is an estimate based on first results of the Malaysian MASS network.

5. Updating the geodetic network for Thailand

Updating the geodetic network for Thailand will not be an easy task. The entire network is still further deforming as a result of the post-seismic motion. In order to compute new station coordinates two different approaches need to be used, which are formulated in in Eq. 1 and 2 : one before the earthquake, and one after the earthquake.

Before the earthquake:
$$pos(t) = pos_{ref} + (t - t_{ref}) . vel \qquad (1)$$
After the earthquake:
$$pos(t) = pos_{ref} + (t - t_{ref}) . vel + disp_{co-seismic} + disp_{post-seismic} (loc, t - t_{quake}) \qquad (2)$$
where

$pos(t)$	= station position at time t (x,y,z)
pos_{ref}	= reference station position
t	= time
t_{ref}	= time of reference point (*e.g* 25/12/04)
vel	= station velocities (x', y',z')
$disp_{co-seismic}$	= co-seismic displacement at station location (constant)
$disp_{post-seismic}$	= post-seismic displacement at station location (time dependent)
t_{quake}	= time of earthquake

In case coordinates need to be computed before the earthquake, the station coordinates given at the reference date (e.g. 25/12/04) can be corrected using the continuous station motions (Appendix A).

However after the earthquake, it becomes more complicated, and not all the required information to use Eq. 2 is presently known. The first 2 parts of Eq. 2 are equal to Eq. 1 and the co-seismic displacements required for the 3rd part have been measured, and can be modeled at any location in Thailand. This was done already in the framework of the SEAMERGES project, based on the co-seismic motions at almost 60 GPS locations in SE Asia (Vigny et al., 2005), which also includes the GPS measurements discussed in this report. The model results are shown in Fig. 5. The model also clearly shows the deformation pattern throughout SE Asia, and confirms that in Thailand the Island of Phuket and nearby regions are most affected. Near the boundaries with Myanmar and Laos, more than 1500 km away from the earthquake epicenter, the landscape still has shifted by at least 2 cm. The model also shows that the co-seismic displacements outside Thailand reached up to 2 meter in the Northern tip of Sumatra, and up to 5 meter at the Andaman and Nicobar Islands.

The final part of Eq. 2 presently cannot be used to predict positions after the latest GPS measurements. The final post-seismic deformation pattern will most probably look very similar to the one of Fig. 5. However, where the co-seismic motion took place within 10 minutes and is constant for a given location, the post-seismic motion can go on for years. The exponential decay rate can only be estimated accurately by monitoring the post-seismic motions over a large time period. Although campaign-style measurements are useful when the post-seismic rates are still high, a network of permanent GPS stations
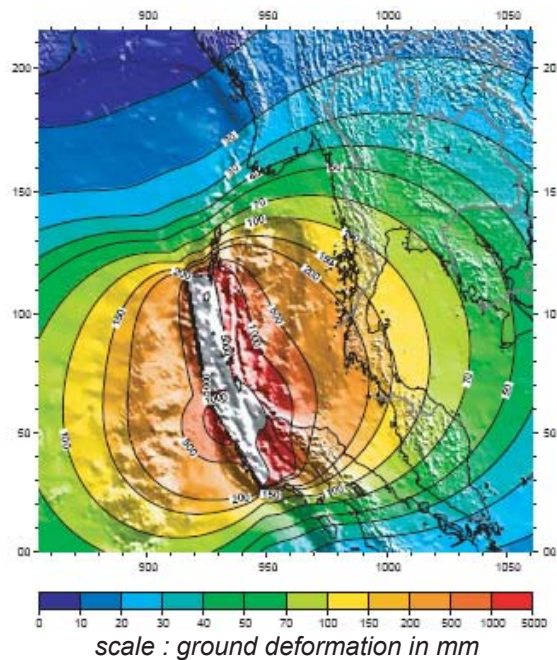
scale : ground deformation in mm

Fig. 5 Co-seismic deformation in S.E. Asia due to 26/12/04 earthquake

will be more suited. Currently, permanent GPS data is only directly available to RTSD and DEOS from the semi-permanent GPS station RYNG in Rayong, which will kept running by DEOS as part of the SEAMERGES project until at least the end of 2005. Also a new GPS station will be installed by DEOS at RTSD in Bangkok in April 2005, and will be used to monitor the post-seismic deformation in the Bangkok area. It would be very useful to include permanent GPS data of the Department of Public Works and Town Planning, and from the GPS stations managed by the Department of Geology of Chulalongkorn University if these departments are willing to share their data.

At present it is very difficult to estimate how the post-seismic component evolves. Also there is few information on it's final size. For past earthquakes in the range of Mw 7.5-8.0 the post-seismic component equals the co-seismic component (Heki et al., 1997). Therefore the total displacement can reach twice the co-seismic component. But for a Mw 9.3 earthquake, it is not known if this factor holds. The duration and amplitude depends directly on the Earth's mantle viscosity below the affected surface. And these properties are unknown, although we can learn them from monitoring the post-seismic deformation with GPS.

From the latest GPS measurements, it can be observed that after 50 days the total displacement was 1.25 times the initial co-seismic displacement at the Indonesian, Malaysian, Singapore and Thai sites (see previous section, 1/0.80). With this information and the assumption that the exponential decay rate stays the same throughout the entire post-seismic period, it is possible to use the simple law given in Eq. 3 to get some more insight in the behavior of post-seismic motions:

$$disp_t = 2 - \exp^{(t/t_0)} \tag{3}$$

where

$disp_t$	= times co-seismic displacement at time t
t	= time after earthquake (days)
t_0	= constant parameter decay rate (days)

Solving equation 3 first for t_0, with t = 50 days and $disp_{50}$ = 1.25 results in a t_0 factor of -173.8 days. If the exponential decay remains the same, the total displacement will reach 1.87 times the co-seismic motion after 1 year, and 1.98 times the co-seismic motion after 2 year. An overview for 4 Thai sites (PHUK, CHON, SRIS and OTRI) is given in Table 5.

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Table 5. Prediction of future co- and post-seismic displacement

Days	Factor	site displacement (cm)			
		PHUK	CHON	SRIS	OTRI
measured					
0	1.00	27.2	7.8	3.7	3.2
50	1.25	33.9	9.7	4.6	4.0
predicted					
75	1.35	36.7	10.5	5.0	4.3
125	1.51	41.1	11.8	5.6	4.8
200	1.68	45.7	13.1	6.2	5.4
300	1.81	49.2	14.1	6.7	5.8
425	1.91	52.0	14.9	7.1	6.1
575	1.96	53.3	15.3	7.3	6.3
800	1.99	54.1	15.5	7.4	6.4

Although the predicted values are a rough estimate, some important observations can be made. The post-seismic motion is most significant in the first year after the earthquake because it reduces exponentially. Therefore it is very important to repeat the GPS observations at least 2 more times this year, in order to model the post-seismic decay pattern more accurately. A second re-measurement around May (5 months after the earthquake) followed by another observation round in October 2005 (10 months after the earthquake)would be desirable. The post-seismic motion will remain detectable for the longest time period on the island of Phuket, which can reach a total displacement of more than 50 cm. The Bangkok area will shift further up to a total displacement of 15 cm, and the North and East of Thailand will finally reach displacements between 6 and 7 cm. The remaining post-seismic changes will drop below 1 cm in the South after about 1.5 year, and in the North and East after about 0.5 year. As explained earlier on, an accurate prediction of the coordinates for the Thai network after the last campaign is not yet possible. Only the positions at that epoch (50 days after the earthquake) are known and can be found in Appendix B. First additional GPS re-measurements are required to model the post-seismic motion better. Only then complete and accurate time dependent transformation parameters between pre- and post-earthquake network coordinates can be obtained.

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Appendix A: Site Coordinates/Velocities before 26/12/04

Station	ITRF-2000 Coordinates (m)			1-σ Standard Deviations (m)		
	X	Y	Z	X	Y	Z
OTRI	-986191.8595	5975733.4053	1993725.9455	0.0023	0.0056	0.0022
UTHA	-1069535.1464	6057468.9018	1681107.9891	0.0016	0.0051	0.0018
SRIS	-1534865.2019	5971007.1476	1629560.1008	0.0020	0.0056	0.0019
CHON	-1190208.4919	6097682.8063	1438406.3140	0.0018	0.0055	0.0017
BANH	-988985.6170	6191316.3651	1166580.9854	0.0020	0.0072	0.0016
PHUK	-912742.1075	6253870.4355	855385.4175	0.0017	0.0049	0.0012
NAKH	-1079557.4759	6046897.2966	1711940.7059	0.0034	0.0083	0.0027
PATN	-1219178.2562	6216053.6355	742774.0721	0.0225	0.0588	0.0139
RYNG	-1190626.7086	6106577.0960	1400007.2139	0.0050	0.0144	0.0045

Reference date of coordinate solution: 25-DEC-2004
The above standard deviations are (1-σ) values

Station	ITRF-2000 Velocities (mm/yr)			Standard Deviations (mm/yr)		
	North	East	Up	North	East	Up
OTRI	-5.194	+31.395	-0.101	0.326	0.553	1.637
UTHA	-6.814	+33.575	+2.397	0.329	0.441	1.683
SRIS	-8.775	+32.871	+5.132	0.319	0.442	1.634
CHON	-6.534	+32.400	+4.710	0.199	0.296	1.002
BANH	-4.386	+33.695	+2.776	0.279	0.464	1.446
PHUK	-3.042	+33.084	+5.090	0.195	0.309	0.945
PATN	-6.445	+29.341	-29.706	4.358	6.908	23.621
NAKH	-2.389	+32.259	-5.508	1.043	1.697	5.339
RYNG	NA	NA	NA	NA	NA	NA

The above standard deviations are (1-σ) values

Appendix B: Site Coordinates Update on 12/02/05

Station	ITRF-2000 Coordinates (m)			1-σ Standard Deviations (m)		
	X	Y	Z	X	Y	Z
OTRI	-986191.8452	5975733.4493	1993725.9297	0.0031	0.0071	0.0028
UTHA	-1069535.0949	6057468.9129	1681107.9359	0.0017	0.0055	0.0019
SRIS	-1534865.1696	5971007.1657	1629560.0800	0.0024	0.0065	0.0023
CHON	-1190208.4150	6097682.8336	1438406.2678	0.0020	0.0062	0.0020
BANH	-988985.4387	6191316.4225	1166580.8967	0.0023	0.0075	0.0017
PHUK	-912741.8020	6253870.4927	855385.2885	0.0016	0.0052	0.0013
NAKH	-1079557.4339	6046897.3141	1711940.6513	0.0020	0.0063	0.0022
PATN	NA	NA	NA	NA	NA	NA
RYNG	-1190626.6235	6106577.1251	1400007.1693	0.0016	0.0050	0.0016

Reference date of coordinate solution: 12-FEB-2005
The above standard deviations are (1-σ) values

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